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This project carried out an interdisciplinary research program among scientists and students of the Boston Consortium for Behavioral and Neural Studies, which includes investigators from seven Boston-area institutions. Projects concerning the cognitive, perceptual, and neural bases of skilled performance included both experimental and theoretical studies of vision, speech, adaptive pattern recognition, attentive cognitive information processing, reinforcement learning and prediction, and adaptive sensory-motor control and planning. These studies paid particular attention to those properties of biological intelligence that can autonomously adapt in real-time to unexpected events. Major progress was made towards discovering and characterizing neural network architectures in all of the project areas.

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FINAL REPORT

"THE COGNITIVE, PERCEPTUAL, AND NEURAL BASES OF SKILLED PERFORMANCE"

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OCTOBER 1, 1987—DECEMBER 31, 1989

STEPHEN GROSSBERG, PRINCIPAL INVESTIGATOR
CENTER FOR ADAPTIVE SYSTEMS
BOSTON UNIVERSITY
111 CUMMINGTON STREET
BOSTON, MA 02215

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SUMMARY

This project carried out an interdisciplinary research program among scientists and students of the Boston Consortium for Behavioral and Neural Studies, which includes investigators from seven Boston-area institutions. Projects concerning the cognitive, perceptual, and neural bases of skilled performance included both experimental and theoretical studies of vision, speech, adaptive pattern recognition, attentive cognitive information processing, reinforcement learning and prediction, and adaptive sensory-motor control and planning. These studies paid particular attention to those properties of biological intelligence that can autonomously adapt in real-time to unexpected events. Major progress was made towards discovering and characterizing neural network architectures in all of the project areas.

The Boston Consortium engaged in a number of collaborative ventures that crossed both disciplinary and institutional lines. These interactions were facilitated by providing offices for Consortium members at the Center for Adaptive Systems of Boston University. Research appointments and parking privileges at Boston University were also provided to facilitate interactions of faculty from several universities.

For example, Professor James Todd of Brandeis University developed part of his psychophysics lab at Boston University and hired a graduate student in the Boston University graduate program in Cognitive and Neural Systems as an RA. Todd also joined Stephen Grossberg, Ennio Mingolla, and Dejan Todorović of Boston University in a research seminar on motion perception that led to a great deal of new research. Professor Paola Bressan of Padua University visited Boston University for a year, and could thus carry out an experimental collaboration with James Todd as well as with Michael Rudd, who is a Boston University postdoctoral fellow. Bressan and Rudd experimentally tested, with positive results, theoretical predictions of the neural network motion perception model of Stephen Grossberg, Ennio Mingolla, and Michael Rudd. James Todd and Robin Akerstrom of Brandeis also successfully tested predictions about 3-D shape-from-texture from the neural network model of visual form perception that was developed by Grossberg and Mingolla.

Professor Adam Reeves of Northeastern University joined Michael Rudd and Stephen Grossberg in a theoretical analysis of temporal properties of peripheral vision, notably transient tritanopia, in which Reeves is a leading experimentalist. Reeves also experimentally tested the prediction of Gail Carpenter and Stephen Grossberg that an attentional gain control channel helps to control attentional priming and visual pattern recognition. Reeves, with Larry Arend of the Eye Research Institute, tested properties of the neural network model of brightness perception under variable illumination that was developed by Grossberg and Dejan Todorović, a Boston University postdoctoral fellow.

Professor John Daugman of Harvard University began neurobiological experiments to test properties of the Grossberg-Mingolla visual form perception theory, also called the Boundary Contour System, or BCS. Daugman also developed an effective texture segmentation algorithm for image processing that uses some BCS mechanisms, as well as a neural network model for learned orthogonalization of non-orthogonal complete representations for image processing, which is closely related to the scheme for adaptive coordinate change that was developed by Grossberg and Michael Kuperstein, then a Boston University postdoctoral fellow, for use in adaptive sensory-motor control. Michael Kuperstein has since founded a company called Neurogen to build adaptive robots whose controllers are based upon his research with Grossberg.

A wide variety of such productive interactions has developed during the URI grant period, and have contributed to a lively URI-based intellectual community in Boston. The cooperative organization of this community has made it possible for its members to initiate and develop a large number of research ties with universities, as well as government and industrial laboratories throughout the United States and abroad. For example, neural network models developed at the Center for Adaptive Systems are now being used in cutting-edge

applications to vision. speech and radar. pattern recognition. and robotics around the world.

The dynamism of this community also enabled it to play a key role in helping to develop an infrastructure for international cooperation in neural network research and education. These contibutions include founding the International Neural Network Society, founding the journal *Neural Networks*, and helping to organize the IEEE First International Conference on Neural Networks.

More detailed summaries of URI activities are provided below.

PART I

Boston University Summary:

Research at the
Center for Adaptive Systems
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1. PUBLICATIONS PARTIALLY SUPPORTED BY THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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2. ADAPTIVE RESONANCE THEORY: SELF-ORGANIZING NEURAL NETWORKS FOR PATTERN RECOGNITION IN A NONSTATIONARY WORLD

Gail A. Carpenter

Articles A

1. Carpenter, G.A. and Grossberg, S., ART 2: Self-organization of stable category recognition codes for analog input patterns. *Proceedings IEEE First International Conference on Neural Networks*, **II**, (1987) 727–735.

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Articles C

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A. ART 2: Stable self-organization of pattern recognition codes for analog input patterns (Articles A)

Adaptive resonance architectures are neural networks that self-organize stable pattern recognition codes in real-time in response to arbitrary sequences of input patterns. These articles introduce and develop ART 2, a class of adaptive resonance architectures which rapidly self-organize pattern recognition categories in response to arbitrary sequences of either analog or binary input patterns. The architecture incorporates many new features beyond those present in the ART 1 systems, which establish recognition categories for binary input patterns (Carpenter, G. A. and Grossberg, S., *Computer Vision, Graphics, and Image Processing*, **37**, 54–115, 1987). In order to cope with arbitrary sequences of analog input patterns, ART 2 architectures embody solutions to a number of design principles, such as the stability-plasticity tradeoff, the search-direct access tradeoff, and the match-reset tradeoff. In these architectures, top-down learned expectation and matching mechanisms are critical in self-stabilizing the code learning process. A parallel search scheme updates itself adaptively as the learning process unfolds, and realizes a form of real-time hypothesis discovery, testing, learning, and recognition. After learning self-stabilizes, the search process is automatically disengaged. Thereafter input patterns directly access their recognition codes without any search. Thus recognition time for familiar inputs does not increase with the complexity of the learned code. A novel input pattern can directly access a category if it shares invariant properties with the set of familiar exemplars of that category. A parameter called the attentional vigilance parameter determines how fine the categories will be. If vigilance increases (decreases) due to environmental feedback, then the system automatically searches for and learns finer (coarser) recognition categories. Gain control parameters enable the architecture to suppress noise up to a prescribed level. The architecture's global design enables it to learn effectively despite the high degree of nonlinearity of such mechanisms.

B. Invariant pattern recognition: ART modules in network hierarchies (Articles B)

This work illustrates how ART modules may be embedded in neural network hierarchies to perform tasks such as invariant pattern recognition and associative learning.

Article 6 describes a neural network architecture which can

(1) stably self-organize an invariant pattern recognition code in response to a sequence of analog or binary input patterns;

(2) be attentionally primed to ignore all but a designated category of input patterns;

(3) automatically shift its prime as it satisfies internal criteria in response to the occurrence of a previously primed category of input patterns;

(4) learn to generate an arbitrary spatiotemporal output pattern in response to any input pattern exemplar of an activated recognition category.

This architecture exploits properties of the ART 1 and ART 2 adaptive resonance theory architectures, and uses a simple preprocessing system based upon the Boundary Contour System (BCS) for boundary segmentation (Grossberg, S. and Mingolla, E., *Perception and Psychophysics*, **38**, 141–171, 1985). The system is used to carry out self-organizing, invariant pattern recognition of noisy, multisensor laser radar images.

Article 4 describes recent progress on this research project. In particular the preprocessing stages have been developed to improve recognition of images with high noise levels.

while retaining the rapid performance of a feedforward preprocessor. The new circuit for boundary segmentation, called the CORT-X filter, detects, regularizes, and completes sharp (even one-pixel wide) image boundaries in up to 50% noise, while simultaneously suppressing the noise. The CORT-X filter achieves this competence by using nonlinear interactions between multiple spatial scales to resolve a design trade-off that exists between the properties of boundary localization, boundary completion, and noise suppression. The processing levels of the CORT-X filter are analogous to those of the Boundary Contour System, but contain only feedforward operations that are easier to implement in hardware. The network nodes in these levels are analogous to cortical simple cells, complex cells, hypercomplex cells, and unoriented and oriented cooperative cells.

Articles 3, 6, and 7 outline how ART recognition modules can be embedded in neural network architectures that include recall and reinforcement capabilities. The articles indicate how well-developed individual network modules can be linked to perform higher-order functions, including motor output.

C. Comparative analysis and development of neural network systems (Articles C)

These articles share a goal of analysing various neural network models by identifying common themes. Identification of a core module facilitates comparative analysis of different models' capabilities.

Review article 8 outlines some fundamental neural network modules for associative memory, pattern recognition, and category learning. Included are discussions of the McCulloch-Pitts neuron, perceptrons, adaline and madaline, back propagation, the learning matrix, linear associative memory, embedding fields, instars and outstars, the avalanche, shunting competitive networks, competitive learning, computational mapping by instar/outstar families, adaptive resonance theory, the cognitron and neocognitron, and simulated annealing. Adaptive filter formalism provides a unified notation. Activation laws include additive and shunting equations. Learning laws include back-coupled error correction, Hebbian learning, and gated instar and outstar equations. Also included are discussions of real-time and off-line modeling, stable and unstable coding, supervised and unsupervised learning, and self-organization.

Article 9 describes models of associative pattern learning, adaptive pattern recognition, and parallel decision-making by neural networks. It is shown that a small set of real-time nonlinear neural equations within a larger set of specialized neural circuits can be used to study a wide variety of such problems. Models of energy minimization, cooperative-competitive decision making, competitive learning, adaptive resonance, interactive activation, and back propagation are discussed and compared.a

Article 10 shows how applications of techniques from physics, such as energy minimization, that have been used in neural network analysis are special cases of more general results in the neural network literature.

D. ART 3: Hierarchical search using chemical transmitters in self-organizing pattern recognition architectures (Articles D)

Articles 11 and 12 introduce and begin development of a new research project. The ART 3 model implements parallel search of compressed or distributed pattern recognition codes in a neural network hierarchy. The ART 3 search process functions well with either fast learning or slow learning, and can robustly cope with asynchronous processing of arbitrary sequences of input patterns in real-time. The search process emerges when computational properties of the chemical synapse, such as transmitter accumulation, release, inactivation, and modulation, are embedded within an ART 2 architecture. Formal analogs of ions such as Na^+ and Ca^{2+} control nonlinear feedback interactions that enable presynaptic transmitter dynamics to model the postsynaptic short term memory representation of a pattern recognition code. Reinforcement feedback can modulate the search process by altering the ART 3 vigilance parameter or directly engaging the search mechanism. The search process is a form of hypothesis testing capable of discovering appropriate representations of a nonstationary input environment.

This work indicates solutions to computational bottlenecks which can occur when nonlinear adaptive feedback modules, such as ART, are embedded in neural network hierarchies. In particular, computation is required to be robust and asynchronous but also capable of rapid reset.

3. SUMMARY OF NEURAL NETWORK RESEARCH

Stephen Grossberg

(A) Some Earlier Research Accomplishments

1. A Self-Organizing Neural Network Architecture for Invariant Pattern Recognition and Nonstationary Hypothesis Testing

Gail Carpenter and Stephen Grossberg have analysed how *arbitrary* time series of *analog or digital* input patterns can be automatically categorized and recognized by a real-time Adaptive Resonance Theory (ART) architecture. called ART 2. Such an architecture has been shown to possess a unique set of computational properties relative to other adaptive pattern recognition techniques. See Table 1 for a summary. In particular. ART 2 is an autonomous hypothesis testing and pattern recognition machine that is capable of self-organizing, self-stabilizing. and self-scaling its learned recognition code. It is capable of directly accessing these codes after learning occurs. Before that happens. an efficient self-adjusting parallel memory search helps to discover a globally self-consistent recognition code during the learning phase.

Subsequent to the initial phase of this work. three variations of the ART 2 architecture were developed, all of them exhibiting the properties outlined in Table 1.

With these architectures in hand. a system was designed that is capable of *invariant* visual pattern recognition. As in many applications of ART 2, a specialized preprocessor was designed to transform image data before the ART architecture received it. In this application, Carpenter and Grossberg first worked with Paul Kolodzy and Steve Rak of MIT Lincoln Labs. Courosh Mehanian has since joined Carpenter and Grossberg to develop a more advanced system.

This application uses a laser range detector to compute image distance and a laser doppler detector to compute image velocity. Intersecting the outputs of these detectors automatically separated image figure from ground.

The separated figure was then passed through a simplified version of a neural network that was developed by Grossberg and his colleague Ennio Mingolla. The Grossberg-Mingolla Boundary Contour System (BCS) detects, sharpens, regularizes, and completes image boundaries, while suppressing image noise.

These boundary representations were then passed through a Fourier-Mellin filter to generate spectra that are invariant under 2-dimensional image rotation, dilation, and shift.

These invariant spectra of boundary-completed laser radar images were the inputs to the ART 2 system. The ability of ART 2 to classify any set of analog imagery made this application possible.

Present work is further refining the ART 2 architecture, notably towards building a many-level hierarchical ART system capable of simultaneously encoding an input pattern's most salient parts, and towards developing the system to cope with high levels of image noise (20%–50%).

2. A Neural Network Architecture for Self-Organization of Speech Perception and Production Codes

This project was undertaken through collaboration of Michael Cohen. Stephen Grossberg. and David Stork. It has led to the articulation of a new neural network architecture, the significance of which is now summarized. Considerations of the real-time self-organization of neural networks for speech recognition and production led to a new understanding of several key designs for such networks which clarify how variable-rate speech sounds of different speakers in noise may be coherently completed and recognized in real-time. Among

TABLE 1

ART Architecture	Alternative Learning Properties
Real-time (on-line) learning	Lab-time (off-line) learning
Nonstationary world	Stationary world
Self-organizing (unsupervised)	Teacher supplies correct answer (supervised)
Memory self-stabilizes in response to arbitrarily many inputs	Capacity catastrophe in response to arbitrarily many inputs
Effective use of full memory capacity	Can only use partial memory capacity
Maintain plasticity in an unexpected world	Externally shut off plasticity to prevent capacity catastrophe
Learn internal top-down expectations	Externally impose costs
Active attentional focus regulates learning	Passive learning
Slow or fast learning	Slow learning or oscillation catastrophe
Learn in approximate-match phase	Learn in mismatch phase
Use self-regulating hypothesis testing to globally reorganize the energy landscape	Use noise to perturb system out of local minima in a fixed energy landscape
Fast adaptive search for best match	Search tree
Rapid direct access to codes of familiar events	Recognition time increases with code complexity
Variable error criterion (vigilance parameter) sets coarseness of recognition code in response to environmental feedback	Fixed error criterion in response to environmental feedback
All properties scale to arbitrarily large system capacities	Key properties deteriorate as system capacity is increased

the novel circuits that are being further developed are: the characterization of networks of invariant auditory feature detectors that can process co-articulated consonant and vowel sounds in a speaker-independent fashion: the analysis of networks whereby a partially compressed auditory code is associatively mapped into articulatory commands in a manner that permits imitation and code formation of novel sounds: the design of top-down articulatory-to-auditory priming signals that self-stabilize the learning of this imitative map. and provide understanding of how speech is encoded by how it would have been produced (e.g.. motor theory); the further compression of these motorically modified auditory codes into item codes (e.g.. phonemic segments): the design of a working memory for sequences of item codes, which is able to automatically adjust itself to cope with variable speech rates and to store its items in real-time in a way that preserves the stability of subsequent learning processes; the grouping of item subsequences from working memory into compressed codes, or chunks. by a masking field level whose top-down signals contextually complete and organize the items in working memory into coherent groupings. as in phonemic restoration and word superiority effects. The emergent resonant wave that defines these bottom-up and top-down influenced working memory groupings through time defines a speech code with speaker- and rate-independent invariant properties. This total architecture sheds new light on key speech issues such as coarticulation. analysis-by-synthesis, motor theory, categorical perception. invariant speech perception. word superiority. and phonemic restoration.

3. Control of Predictive Performance by Self-Organizing Recognition-Reinforcement Networks

A key problem in the neural network literature concerns how sensory and cognitive recognition codes interact with reinforcement mechanisms to modulate the learning of recognition codes. This interaction reorganizes recognition codes based upon the success or failure of actions based upon the recognition event. Reinforcement calibrates whether the action has or has not satisfied internal system criteria. Reinforcement mechanisms modify the formation of recognition codes and shift attention to focus upon those codes whose activation has, in the past, generated actions that have satisfied internal system criteria.

A number of other learning models, such as back-propagation, have lumped together the processes of recognition and reinforcement into a single mechanism. Such a step prevents a model from achieving autonomy and stability of learning in a statistically general input environment, as indicated in Table 1. A central problem of neural network theory is to sharply distinguish recognition and reinforcement mechanisms, and to design their feedback interactions to achieve the modulatory properties just described.

An invaluable guide in this design process is the huge data base concerning classical and instrumental conditioning that has accumulated over the past half-century. As of this writing, the conditioning theory being developed at CAS has provided principled explanations and predictions of an order of magnitude more data than alternative theories in this area. Its computational power is also correspondingly more advanced. This theory is realized by a specialized, hierarchically organized ART model. Recent articles have further developed this theory through mathematical analyses and extensive computer simulations, which have enhanced the theory's explanatory and predictive range. Stephen Grossberg, Daniel Levine, and Nestor Schmajuk completed the first phase of this work.

4. Planned Arm Movements and Eye-Arm Coordination

Daniel Bullock and Stephen Grossberg have shown how to design a real-time neural network, called the VITE model (Vector Integration to Endpoint) for flexible, adaptive arm movement control, whereby multijoint trajectories can be performed with synchronous and invariant properties at variable speeds and quickly updated without experiencing combinatorial explosion or programming rigidity. These results have clarified how to begin to design self-organizing associative maps to control eye-hand coordination.

5. Multiple Scale Automatic Encoding of Distributed Data Patterns

Michael Cohen and Stephen Grossberg have shown how to design a masking field neural architecture; viz., a multiple-scale self-similar automatically gain-controlled cooperative-competitive feedback network capable of generating predictive representations of uncertain distributed data, and therefore suggesting a solution to the credit assignment problem.

6. Decision Making under Risk

Stephen Grossberg and William Gutowski have developed a model of neural mechanisms of decision making under risk, that explains paradoxical phenomena such as preference reversals and Gambler's Fallacy.

7. Emergent Segmentation of Noisy Images

Stephen Grossberg and Ennio Mingolla have demonstrated how the Boundary Contour System (BCS) can regularize and complete sharp image boundaries from noisy image data in a self-scaling manner. This demonstration suggests a new approach to penetrating camouflage. The BCS has been used to explain and predict a large body of psychophysical and neurophysiological data about preattentive vision, notably about texture segmentation, shape-from-shading, binocular fusion and rivalry, and illusory contours. It has influenced the work of many experimental laboratories, and an increasing number of its predictions have been supported by experimental tests.

8. Multiplexed Multiscale Fusion of Image Features

Stephen Grossberg and Jonathan Marshall have shown how to design an adaptive filter for stereoscopic image fusion that multiplexes image data about position, orientation, spatial frequency, and binocular disparity.

9. Perception in Variable Illumination

Stephen Grossberg and Dejan Todorović have developed the 2-D Feature Contour System (FCS) that was earlier proposed in the 1-D case by Cohen and Grossberg. They have shown through extensive computer simulations how the model can explain a large number of visual percepts concerning brightness perception, and more generally the mechanisms whereby the brain can automatically compensate for variable illumination conditions and fill-in surface properties. Grossberg has outlined the 3-D theory whereby surface properties of brightness, color, and depth are filled-in. Ken Johnson at Hughes Aircraft Company has used the model to reconstruct badly distorted infrared images of realistic scenes.

(B) Some Recent Research Projects

1. Continuous Speech Perception and Production

Michael Cohen and Stephen Grossberg have been developing a simulated filter bank as the first stage of speech preprocessing in the neural model for continuous speech perception. The filter will supply signals to subsequent processing stages that model the eighth nerve and its target neural interactions. These stages disambiguate coarticulated consonant and vowel sounds based upon such properties as their coherence, before the disambiguated signals are compressed into acoustic features.

Cohen and Grossberg are also modelling fundamental properties of the speech code; for example, how the speech code can automatically adjust its time scale and can complete locally ambiguous data by using top-down learned expectations. These results clarify how to avoid limitations of time warping techniques in dynamic programming. They also clarify how speech signals from subsequent words can disambiguate speech signals from previous words while sharpening, rather than obfuscating, word boundaries, and without disrupting the conscious ordering of perceived speech from past to future words.

2. Adaptive Pattern Recognition

Gail Carpenter and Stephen Grossberg have been further developing Adaptive Resonance Theory (ART) architectures for self-organization of distributed hypothesis testing and pattern recognition in response to nonstationary streams of input patterns. They have simulated a new mechanism, called ART 3, for parallel search and hypothesis testing within a network hierarchy. This mechanism is capable of appropriately adjusting the activities and adaptive weights of distributed network codes in response to disconfirmation of a hypothesis about the input pattern. The search mechanism uses neural mechanisms of chemical transmission and nonlinear signal transduction that were not previously realized to be capable of supporting a parallel hypothesis testing cycle.

3. Reinforcement Learning and Adaptive Timing

Stephen Grossberg and John Merrill have been developing neural models capable of automatically learning to time goal-oriented actions within a reinforcement learning paradigm. Such a competence is necessary to enable animals, humans, or freely-moving robots to generate actions that are appropriately delayed in order to successfully obtain goal objects under real-time conditions. The results promise to shed new light upon how the hippocampus, hypothalamus, septum, and cortex are designed and interact. They should also prove useful in the design of freely moving adaptive robots.

4. Visual Motion Segmentation

Stephen Grossberg, Ennio Mingolla, and Michael Rudd are developing a neural architecture, called a Motion Boundary Contour System, for visual motion segmentation. Such an architecture clarifies why parallel circuits for static segmentation and motion segmentation are needed, by computationally characterizing novel properties of the motion segmentation circuit that cannot be computed by a static segmentation circuit. The architecture will be useful for generating coherent representations of rapidly moving objects under noisy viewing conditions. It has bee used to explain a large body of classical and recent data about apparent motion, motion capture, induced motion, and motion aftereffects that other motion models have been unable to explain.

5. Adaptive Robotics

Daniel Bullock and Stephen Grossberg are developing a model, called the FLETE model (**F**actorization of **LE**ngth and **TE**nsion) to explain how neural commands can generate accurate goal-oriented arm movements despite perturbations by variable forces and the inertias generated by variable speeds. The model explains how accurate arm positions can be commanded at a wide range of arm tensions. In so doing, it suggests a computational explanation of spino-muscular circuit elements, such as the size principle and Renshaw cells, that have been mysterious for a long time. The FLETE model should also be useful for the control of artificial robot arms.

6. Self-Organization of Motor Controllers

Stephen Grossberg and Paolo Gaudiano have been developing a neural model for a self-organizing neural controller to generate synchronous trajectories of multiple limb components. This work builds upon earlier work of Bullock and Grossberg which introduced and analysed the VITE model (Vector Integration To Endpoint) for generating synchronous limb trajectories, notably for arm movements and speech articulator movements. The present research is studying how a VITE-type model can determine its own best parameters to generate optimal control of limb trajectories. The results have begun to show how the system can spontaneously generate actions that serve as a basis for testing its own parameters and adjusting them through learning until they are optimized.

4. NEURAL NETWORK MODELS OF MOTION PERCEPTION

Ennio Mingolla

In collaboration with Stephen Grossberg. Ennio Mingolla has been developing a neural architecture for segmentation and grouping of moving image contours. The model clarifies how preprocessing of motion signals by a Motion Oriented Contrast (MOC) Filter is joined to long-range motion mechanisms in a motion Cooperative-Competitive Loop to control phenomena such as induced motion, motion capture, and motion after-effects. The total model system is a motion Boundary Contour System (BCS) that is computed in parallel with the static BCS of Grossberg and Mingolla before both systems cooperate to generate a boundary representation for 3-D visual form perception. The model clarifies how the BCS used in static segmentation problems can be modified for use in motion segmentation problems, notably for analysing how ambiguous local movements (the aperture problem) on a complex moving shape are suppressed and actively reorganized into a coherent global motion signal. Unlike many previous approaches, this work analyses how a coherent motion signal is imparted to all regions of a moving figure ("motion capture"), not only regions at which unambiguous motion signals exist.

Mingolla has also been collaborating with Bryant York of the Boston University Computer Science Department on the development of a Connection Machine implementation of the BCS. Besides the intrinsic importance of this work within the field of parallel computation, the implementation promises to be a key tool in the development of more detailed specification of BCS architectures for a number of important visual phenomena, including multiple-scale effects in textural segmentation and grouping, binocular fusion and rivalry, and for the use of the BCS on natural images.

Mingolla has continued to consult regularly with Michael Rudd and with James Todd on their investigation of motion perception and surface perception. He has given several colloquium presentations and three invited talks at international meetings on work sponsored by the present grant.

5. RELATED ACTIVITIES AT THE CENTER FOR ADAPTIVE SYSTEMS

1. Patents

The vision patent for the Boundary Contour System of Stephen Grossberg and Ennio Mingolla was approved. It was written up in a featured article in the New York Times patent section. A pattern recognition patent for ART 2 of Gail Carpenter and Stephen Grossberg was also approved, as was a robotics patent of Stephen Grossberg and Michael Kuperstein.

2. International Neural Network Society and IEEE International Conference on Neural Networks

Stephen Grossberg founded and served as first president of INNS. During his presidency, members joined at the rate of over 200 per month, reaching a total of 3,800 when he left office. Over 600 speakers and 1700 attendees were present at the INNS first annual meeting held in Boston in September, 1988.

Grossberg was also general chairman of the IEEE First International Conference on Neural Networks (ICNN) that was held in June, 1987. He and Center colleagues played a major role in setting up and carrying out the procedures for this large and successful meeting. In 1989, the ICNN and INNS meeting fused into the IEEE/INNS International Joint Conferences on Neural Networks (IJCNN). Thus the Center played a central role in setting up this major intellectual resource.

3. Neural Networks Journal

Stephen Grossberg founded and is co-editor-in-chief of the INNS journal *Neural Networks*, which is published by Pergamon Press. The journal went from 4 issues in 1988 to 6 issues in 1989. It is widely respected as the best journal in the field.

4. Graduate Program in Cognitive and Neural Systems

This Ph.D. and M.A. granting program admitted its first students in September, 1988. It developed a systematic graduate curriculum of eight new courses that cover all aspects of neural network research. Students also take a concentration of eight carefully selected courses in a core department, such as computer science or mathematics. Six professors were hired into the program in 1988–89.

The 1988 and 1989 graduate students total 40. The quality of these student classes is very high. A number of the students have already begun to do neural network research in collaboration with a faculty advisor.

5. Endowed Wang Chair

An Wang, founder of Wang Laboratories, gave an endowed chair to Boston University, which has been awarded to Stephen Grossberg.

6. Use of Center Work

Many University researchers, companies, and government labs have been applying or further developing neural architectures invented at the Center for Adaptive Systems, notably our architectures for vision, pattern recognition, hypothesis testing, CAM, and robotics. Also, a growing number of laboratories are successfully testing biological predictions made in these models. These groups include MIT Lincoln Laboratory, Wright-Patterson Air Force Base, JPL, Hughes, BP, Booz-Allen & Hamilton, Martin-Marietta, Raytheon, Boeing, TRW, SAIC, Texas Instruments, HNC, NRL, U.S. Army Missile Command, and Joint Institute for Laboratory Astrophysics.

7. URI Vision Meeting

A successful URI vision meeting was held at Boston University in March, 1988. Its 15 invited speakers included both URI researchers and distinguished external researchers. The meeting program is found in Appendix A.

8. Research Colloquium

Distinguished scientists lecture weekly as part of a colloquium that is sponsored by the Center for Adaptive Systems and the graduate program in Cognitive and Neural Systems. The colloquium is advertised throughout the Boston area and draws an audience of 60–70 scientists and students from a broad range of Boston-area institutions whose composition varies with the topic. The colloquium announcements are found in Appendix B to illustrate the interdisciplinary range of the speakers and their intellectual distinction.

9. External Invited Lectures

Faculty at the Center for Adaptive Systems give 75–100 invited lectures each year on their research, both in the United States and abroad.

PART II

Northeastern University Summary

FINAL REPORT: AFOSR URI

Adam Reeves
Northeastern University
Department of Psychology
360 Huntington Avenue
Boston MA 02115

Summary of Research

Research was proposed and undertaken in two areas of color vision: surface appearance (with L. Arend) and opponent processes (with S. Grossberg). Work on spatial modelling was also done (with J. Yang).

Arend and I have studied the perceived lightness. brightness. and chroma of Mondrian-like surfaces (Arend and Reeves. JOSA (A) 1743-1751. 1986). This work was continued in the present grant period (Reeves *et al.*. 1988: Arend *et al.*. 1990: Schirillo *et al.*, 1990). We have been primarily interested in mechanisms of constancy (discounting the illuminant). Both the extent of constancy and its causes are debated. Von-Kries adaptation is known to produce good color constancy. but. when adaptation is controlled, in the earlier work we found only reasonable constancy (up to 60% of the maximum possible in UCS space) when subjects match surface appearance ("make the target patch look as if it was cut from the same piece of paper as the corresponding patch"). When they match the color without regard to surface quality (so-called "unasserted" matches). color constancy is residual (less than 20%: Reeves *et al.*. 1988). These results were obtained when the stimuli were steady or flashed. and when they were presented side-by-side or successively. The successive case is particularly important because it answers an objection to our earlier claim that color constancy is not automatic: namely. that the visual system computes the mean illuminant over the entire display. If that were the case. color constancy would not be expected in the simultaneous displays: but it still would be expected in the successive ones. In toto, these results disconfirm models which. like Retinex, automatically discount the illuminant and so cannot account for the unasserted matches.

We have also studies lightness and brightness constancy in displays involving depth. The main result is that lightness judgments depend on the perceived depth relations, as originally shown by Gilchrist. but that brightness judgments are independent of depth (Reeves, Schirillo and Arend. 1987; Schirillo. Reeves and Arend. 1990). This is true with moderate, large. and very large (900:1) contrast ratios, and with two different psychophysical methods (multiple choice and adjustment) with importantly different comparison displays.

The second area of research concerns modelling retinal mechanisms of adaptation and opponency. The data of concern are the PI's earlier measurements of the effects of steady and flickered adaptations on the sensitivity of the Y/B and R/G opponent pathways (Reeves, 1987). While steady adaptation can produce a long-lasting transient desensitization (termed "transient tritanopia" in the Y/B case by John Mollon) just after the field is turned off, this effect does not occur if the adapting field is flickered at 1 Hz during adaptation. This paradoxical result cannot be predicted from the slow time course implied by the standard Pugh and Mollon model of transient tritanopia. An initial two-stage version of Grossberg's gated dipole model shows suitable effects of flicker rate (and of duty cycle). and provides appropriate rebounds (to create transient desensitization) at a slower second-level gate (Reeves, 1988). This work. with Michael Rudd and Stephen Grossberg. is still ongoing.

The third area of work. not originally proposed. grew out of an attempt to analyze the spatial frequency responses of the ERG and VEP for linear and non-linear components. Rather surprisingly. we found that a single linear filter. with a fixed shape, could account for the great majority of pattern ERG data published in the last decade (Yang. Reeves, and Bearse, 1990). whether stimuli were gratings. checks. or stripes. Deviations from linearity were non-systematic. Contrast, presentation frequency, and luminance level had no clear-cut effects across studies, despite strong claims to the contrary. On the other hand, VEPs recorded from the occiput do show non-linear responses (Wu, Armington, Yang, and Reeves, 1990). We have varied check size and check displacement in order to capture one type of non-linearity in the VEP, which we hope to model using a thresholded saturating response function introduced by Grossberg.

This research was undertaken with the collaboration of Lawrence Arend of the Eye Research Institute, Michael Rudd and Stephen Grossberg of CAS, and three graduate students at Northeastern, Jian Yang, Marcus Bearse, and Shuang Wu.

Abstracts Supported by this Grant

Reeves A., Schirillo, J., and Arend, L. (1987). Depth, lightness and brightness of achromatic surfaces. Paper presented at the annual meeting of OSA, October 22, 1987, Rochester, NY.

Reeves, A., Arend, L., and Schirillo, J. (1988). Simultaneous and successive color constancy. *Investigative Ophthalmology and Visual Science*, **29** (ARVO Supplement) 162, 1988.

Reeves, A. (1988). Fundamental mechanisms of color vision. Paper given at the meeting: Visual form and motion perception: Psychophysics, computation and neural networks, Boston University, March 1988.

Reeves, A., Yang, J., and Bearse, M. (1989). Spatial frequency selectivity of the pattern electroretinogram (PERG). *Investigative Ophthalmology and Visual Science*, **30** (ARVO Supplement) 513, 1989.

Wu, S., Armington, J., Yang, J., and Reeves, A. (1990). Linearity and non-linearity of visual responses evoked by pattern displacement. *Investigative Ophthalmology and Visual Science*, (ARVO Supplement), 1990.

Papers Supported by this Grant

Arend, L., Reeves, A., Schirillo, J., and Goldstein, R. (1990). Simultaneous color constancy; Patterns with diverse Munsell values. Under revision: *JOSA (A)*.

Reeves, A. (1987). Transient desensitization of opponent channels: A review. *Die Farbe*, **34**, 89–93.

Schirillo, J., Reeves, A., and Arend, L. (1990). Perceived depth influences lightness, not brightness, of achromatic surfaces. Under revision: *JOSA (A)*.

Yang, J., Reeves, A., and Bearse, M. (1990). Spatial linearity of the pattern electroretinogram. Submitted for publication to *Vision Research*.

PART III

MIT Summary

MASSACHUSETTS INSTITUTE OF TECHNOLOGY *CAMBRIDGE, MASSACHUSETTS 02139*

To: Prof. Stephen Grossberg
Director, Center for Adaptive Systems

From: Whitman Richards

Date: 16 February 1990

RE: AFOSR URI Final
Discovering Visual and Acoustic Patterns

1. Whitman Richards, MIT
Department of Brain and Cognitive Sciences

The aim of our research has been to understand how biological systems can make strong assertions about their external work from very impoverished sense data. Our focus has been principally shape recognition, using representations based upon curvature and singularities of curvature. Our methods for study include both psychophysics and computational modelling and algorithms. Recently, the emphasis has shifted from algorithms that are entirely "bottom up" to those which allow the inclusion of "top down" knowledge. This step is needed to reduce the complexity of problems associated with finding one "correct" interpretation of an image from among the many possible.

Our major advance over the past year has been to define formally what is meant by a "perception". Surprisingly, although perception has been studied for centuries, there has been no definition which is precise enough to capture this notion or "event" as an explicit state in a computer program. Our definition hinges around how our beliefs and knowledge of the world affect the interpretation of our sense data. Given a set of beliefs, a lattice of possible belief states can be created, where the modes in the lattice are labelled by the beliefs which remain valid or invalid. A perception can then be defined as a local maximum in a partial ordering within this lattice.

Over the past three years, the URI grant has helped us in several ways other than just supporting our current research activities, or by allowing us to maintain a modern computer-based laboratory. First, it has fostered useful exchanges with the Boston participants, especially Grossberg at B.U., Todd at Brandeis and Daugman at Harvard. Secondly, it has enabled us to bring additional talent to Boston for short periods, such as Jan Koenderink from Utrecht, Staffan Truve from Sweden, and in a reciprocal arrangement, helped make possible an extremely productive visit for Jack Beusman to Koenderink's lab in Utrecht. And thirdly, the grant has strengthened the bridges between activities in the Brain and Cognitive Sciences and EE-CS, namely, through discussions between W. Richards and C. Searle, and shared students.

2. Campbell Searle, M.I.T.
Department of Electrical Engineering & Computer Science

Our aim has been to understand how precise information about formants can be carried in the auditory nerve. Using the cat auditory nerve as our model system, we have completed a time-domain analysis of the firing rate of over 200 fibers responding to synthetic speech signals. We observe distinct groups of fibers in the neurograms of the firing-rate responses. The intervals between peaks in the firing-rates of the fibers in each group are very similar, and reflect the period of the formant that dominates the group's response. We conclude that the cochlear filters have much shorter impulse responses than the formants to which they respond. Analysis of the intervals between peaks in the firing-rates confirms that these intervals correspond directly to the formant periods. The overall formant estimates are better than those of previous spectral analyses of the neural data, and the details of lower-formant dynamics are precisely tracked. The direct representation of the formant period in the time-domain is contrasted with the diffuse spectral representation of the formant, the dependence of spectral peaks on non-formant parameters, and the distortion of the spectrum by physiological non-linearities. Thus, a time-domain analysis of the responses to complex stimuli can be an important addition to frequency-domain analysis for neural data. Although our findings bear most directly upon cochlear models and the machine processing of speech, they also indirectly suggest extensions to the scale-space approaches used in the study of visual information processing.

List of Publications (1989-present only)

Jepson, A. and Richards, W. (1989) Perception and Perceivers. Presented May 25 at a meeting on Vision and Three Dimensional Representations, University of Minnesota, Minneapolis. [To appear as University of Toronto, Dept. of Computer Science, Technical Report.]

Jepson, A. and Richards, W. (1990) What is a Perception? To be submitted to Cognitive Science journal.

Secker-Walker, H. and Searle, C. (1990) Time domain analysis of auditing nerve fiber firing rates. Journal of the Acoustical Society of America (submitted).

Wilson, H.R. and Richards, W. (1989) Mechanisms of Contour Curvature Discrimination. Journal of the Optical Society of America. A 6, 106-115.

PART IV

Brandeis University Summary

Visual Perception of Smoothly Curved Surfaces

James T. Todd

The research performed on this project was designed to investigate the basic mechanisms by which human observers perceive the structures of smoothly curved surfaces. In natural vision, there are several different properties of optical stimulation from which observers are able to obtain information about an object's 3-dimensional form. These include variations of image motion called optical flow, variations in the size and density of image contours called optical texture, and variations in image intensity called shading. This project employed a variety of psychophysical procedures to empirically investigate how the human visual system combines these different sources of information in order to achieve a perceptual representation of objects in 3-dimensional space. The results of these experiments have also been compared with the theoretical capabilities and limitations of numerous formal algorithms used in machine vision for computing an object's 3-dimensional structure from patterns of optical input. Our results indicate that human perception is much less accurate or precise than existing computational models, but that it is also less dependent on assumed constraints on the structure of the environment.

Publications

Todd, J.T., Reichel, F. & Mingolla, E. (1986). Perception of curved surfaces from shading and occluding contours. Bulletin of the Psychonomic Society, 24, 349.

Todd. J. T., & Akerstrom, R. A. (1987). The perception of three dimensional form from patterns of optical texture. Journal of Experimental Psychology: Human Perception and Performance, 2, 242-255.

Fetters, L. E., & Todd, J. T. (1987). Quantitative assessment of infant reaching movements. Journal of Motor Behavior, 19, 147-166.

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Todd, J.T. (1988). Perceived 3D structure from 2-frame apparent motion. Investigative Opthamology, 29, 265.

Akerstrom, R.A., & Todd, J.T. (1988). Perception of stereoscopic transparency. Perception & Psychophysics, 44, 421-432.

Todd, J.T. (1988). Minimal conditions for the perception of structure from motion. Bulletin of the Psychonomic Society, 26, 476-488.

Todd, J.T. (1989). Models of static form perception. In J.I. Elkind, S.K. Carol, J. Hochberg and B.M. Huey (Eds.), Human Performance Models for Computer-Aided Engineering (pp. 75-88). Washington, D.C.: National Academy Press.

Todd, J.T., & Reichel, F.D. (1989). Ordinal structure in the visual perception and cognition of smoothly curved surfaces. Psychological Review, 96, 643-657.

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Mingolla, E., & Todd, J.T. (1989). Perception of solid shape from shading. In B.K.P. Horn & M.J. Brooks (Eds.), Shape from shading (pp. 402-442). Cambridge, MA: MIT Press.

Braunstein, M., & Todd, J.T. (1990). On the perceptual distinction between artifacts and information. Journal of Experimental Psychology: Human Perception and Performance, in press.

Reichel, F.D., & Todd, J.T. (1990). Perceived depth reversals of smoothly curved surfaces from changes in image orientation. Journal of Experimental Psychology: Human Perception and Performance, in press.

Todd, J.T., & Reichel, F.D. (1990). The visual perception of smoothly curved surfaces from double projected contour patterns. Journal of Experimental Psychology: Human Perception and Performance, in press.

PART V

Harvard University Summary

Final Report, U.R.I.

Harvard Subcontract (J.G. Daugman)

I. Publications partially supported under AFOSR U.R.I. contract:

Monograph:

Daugman, J.G. *Signal Processing by Neural Mechanisms.* Toshiba Endowed Chair Lecture Series, Tokyo Institute of Technology, Department of Computer Science (Inaugural Volume). 249 pages. Tokyo: Tokyo Institute of Technology Press, 1990.

Articles:

Daugman, J.G. (1990) An information-theoretic view of analog representation in striate cortex. In *Computational Neuroscience* (E. Schwartz, editor). Cambridge: M.I.T. Press.

Daugman, J.G. (1990) Brain metaphor and brain theory. In *Computational Neuroscience* (E. Schwartz, editor). Cambridge: M.I.T. Press.

Daugman, J.G. (1989) Entropy reduction and decorrelation in visual coding by oriented neural receptive fields. *I.E.E.E. Transactions on Biomedical Engineering*, **36**, pp. 107-114.

Daugman, J.G. (1989) Non-orthogonal wavelet representations in relaxation networks: image encoding and analysis with biological visual primitives. In *Neurocomputing* (John Taylor, editor). London: Institute of Physics Press.

Daugman, J.G. (1989) Networks for image analysis: motion and texture. *I.E.E.E. Proc. I.J.C.N.N.*, **89** 1-5.

Daugman, J.G. (1988) Complete discrete 2-D Gabor transforms by neural networks for image analysis and compression. *I.E.E.E. Transactions on Acoustics, Speech, and Signal Processing*, **36**, pp. 1169-1179.

Daugman, J.G. (1988) Book Review: *The Adaptive Brain* (S. Grossberg, editor). *Mathematical Biosciences*, **91**, pp. 113-116.

Daugman, J.G. (1988) Relaxation neural network for non-orthogonal image transforms. *I.E.E.E. Proc. I.C.N.N.* **88-I**, pp. 547-560.

Daugman, J.G. (1988) Pattern and motion vision without Laplacian zero-crossings. *Journal of the Optical Society of America - A*, **5**, pp. 1142-1148.

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Daugman, J.G. and Kammen, D.M. (1987) Pure orientation filtering: A scale-invariant image processing tool for perception research and data compression. *Behavior Research Methods, Instruments, and Computers*, **18**, pp. 559-564.

Kammen, D.M., and Yuille, A.L. (1988) Spontaneous symmetry-breaking energy functions and the emergence of orientation selective cortical cells. *Biological Cybernetics* **59**, pp. 23-31.

Ph.D. Dissertations supported by U.R.I.:

Kammen, Daniel M. *Self-Organization in Neural Networks.* (Supervisor: J.G. Daugman). Physics Department, Harvard University. Ph.D. awarded June 1988.

Lee, Tai-Sing. *Representation, Generation, and Coordination of Computational Maps in Primate Striate Cortex.* (Supervisor: J.G. Daugman). Engineering Sciences Department, Harvard University. Ph.D. expected June, 1991.

Zheng, Liu. *Neural Encoding of Motion in Fly Lobula Plate.* (Supervisor: J.G. Daugman; masters paper). Engineering Sciences Department, Harvard University. Ph.D. expected June, 1992.

Noteworthy prize-winning undergraduate Theses also supported by U.R.I.:

O'Reilly, Randall C. *Properties of a Self-Organizing Neural Network: The Unsupervised Generation of Hierarchical Representations.* (Supervisor: J.G. Daugman). Earned B.A. *Summa Cum Laude*, Harvard University, 1989. Won Hoopes Prize, as well as Harvard Faculty Prize.

Seybold, John L.C. *Connectionist Theory of Human Categorization Based on Hopfield Networks.* (Supervisor: J.G. Daugman). Earned B.A. *Summa Cum Laude*, Harvard University, 1988. Won Harvard Faculty Prize and Rhodes Scholarship.

II. Summary of Research Progress:

(a). Invertebrate Neural Mechanisms of Figure / Ground Segregation (see Videotape)

The rich visuo-motor behavioral repertoire of simple invertebrates can be elicited by motion discontinuities in the visual field. The demarcation of different velocity vector fields in the retinal stimulus array, even in the absence of any other cues (luminance, contrast, density, chrominance, disparity), constitutes a sufficient cue for visual figure/ground segregation. With physical motion through the environment over time, such discontinuities in the retinal velocity vector field can reveal the 3-D spatial configuration of the environment.

The Harvard group has built a neurophysiology laboratory for recording from isolated neurons in the lobula plate of the Sarcophagus Blowfly, stimulated visually with figure/ground moving texture fields. We use conventional recording techniques but novel stimulation hardware of our own design, duplicate copies of which have recently been installed also in the world's leading invertebrate neural laboratories (Reichardt in Tübingen, and Horridge in Canberra). The dedicated hardware, which is built into Programmable-Logic Array chips clocked at 30 Megahertz, permits the generation of different 2-D velocity vector fields in different image regions. The very fast 30 Megahertz clock permits a high frame rate of 200 Hz, which is a prerequisite for generating smooth motion displays. Both "figure" and "ground" texture fields, defined by specified boundaries, can be assigned any 2-D velocity vector field.

The fly visual system processes motion in Cartesian vector form. Two orthogonal classes of motion neurons, V(ertical) and H(orizontal) cells, exist in the lobula plate. Each one integrates motion cues across the entire contralateral retina, in the form of vector projections onto these two basis vectors. By generating moving texture fields whose two Cartesian velocity vector coordinates can be independently manipulated, we have been able to study the interactions between the vertical and horizontal motion vector coordinates in the neural matrix. Specifically, we have measured the firing rates of individual lobula plate neurons stimulated by moving texture fields whose velocity vectors have the form $S_1 = (v_x, v_y)$, $S_2 = (v_x, 0)$, and $S_3 = (0, v_y)$. All three velocity fields have different speeds and different directions of motion, but S_1 and S_2 have the same horizontal component of motion, while S_1 and S_3 have the same vertical component of motion. Thus the classical framework for understanding the fly visual motion system predicts the same response from an H neuron for stimuli S_1 and S_2, and the same response from a V neuron for stimuli S_1 and S_3, despite all the differences among these stimuli in speeds and directions. We have shown that this is true over small angles, but we have been able to demonstrate definitive inhibitory interactions between the vertical and horizontal motion systems over larger angles. Thus Cartesian vector projection of the independent velocity vector components onto the H and V neural sub-systems is not an adequate model, and competitive interactions must be incorporated.

(b). Studies of Human Visual Motion Perception (see Videotape)

An apparent paradox exists in motion-based visual figure/ground segregation. The measurement of motion in the stimulus array requires an interval of time and a region of space, with greater uncertainty in the motion estimate resulting from the narrowing of either of these. However, we perceive motion discontinuity boundaries as phenomenally sharp, even with very small difference vectors between the two velocity fields. (See videotape). There should be an uncertainty principle limitation here. How can the visual system make a precise measurement of 2-D velocity vector fields, and simultaneously assign a crisp boundary in space (and in time) to the discontinuity between the two velocity signals?

We have investigated the parameters of motion-based figure/ground segregation in human observers. Using only velocity cues, with all other parameters of the moving texture fields identical, we have measured the magnitudes of the differences in speed and/or direction between the two motion vectors necessary to produce a figure/ground percept. These tend to be Weberian (differential signal proportional to vector norm). However, there are significant differences between the efficacy of a *speed* differential, and the efficacy of a *direction* differential, in producing a figure/ground segregation percept. We have also begun to map out the necessary and sufficient vector differentials for driving a *filling in* process based on the differential velocity vector field, versus only seeing the 1-D boundary contour.

A parallel research project now underway concerns the perception of XOR'ed moving texture fields. This is a new form of motion transparency, in which two 2-D moving binary texture fields are combined through the Exclusive-OR boolean operator (essentially multiplicative, rather than additive) by our special 30 Megahertz hardware. The very fact that two independent motion fields can be seen at all is noteworthy, since such stimuli contain absolutely no Fourier motion energy in any direction. Nonetheless, the dual motion percepts are utterly salient. Thus this novel motion stimulus has considerable theoretical significance; no existing motion models appear to be capable of capturing it. We have begun to map out the differential vector parameters which are necessary and sufficient to drive this new class of motion transparency percept.

Finally, as another challenge to existing motion models, we generated a counter-example to the popular ("M.I.T.") model of motion mechanisms based on the movement of Laplacian zero-crossings within the stimulus array. (See "Pattern and Motion Vision without Laplacian Zero-Crossings," *JOSA 1988*.) We generated families of moving textures which, at all spatial scales of analysis, have only stationary Laplacian zero-crossings. Convolution of these spatio-temporal stimuli with $\nabla^2 G_\sigma(x,y)$ operators, of all different blurring scales σ, produces an output all of whose zero-crossings are exactly stationary. Nonetheless, the motion of the stimulus is clearly perceived.

(c). Relaxation Computation of Non-Orthogonal Image Transforms

It is often desirable in image processing to represent image structure in terms of a set of coefficients on a family of expansion functions. For example, familiar approaches to image coding, feature extraction, image segmentation, statistical and spectral analysis, and compression, involve such methods. It has invariably been necessary that the expansion functions employed comprise an orthogonal basis for the image space, because the problem of obtaining the correct coefficients on a non-orthogonal set of expansion functions is usually arduous if not impossible. Oddly enough, image coding in biological visual systems clearly involves non-orthogonal expansion functions. Indeed, it would be nearly impossible to satisfy the rigid constraints of precise control over center positions, weighting structure, and overlap factors, that orthogonality would require of receptive fields, given their notorious "scatter" in all of these parameters. The receptive field profiles of visual neurons with linear response properties typically have large overlaps and large inner products, and are suggestive of a conjoint (spatial and spectral) "2-D Gabor representation." The 2-D Gabor transform has useful decorrelating properties and provides a conjoint image description resembling a speech spectrogram, in which local 2-D image regions are analyzed for orientation and spatial frequency content, but its expansion functions are non-orthogonal. We have developed a general-purpose three-layered relaxation "neural network" that efficiently computes the correct coefficients for this and other, non-orthogonal, image transforms. Examples of applications in image analysis include: (1) image compression to around 0.3 bit/pixel; and (2) textural image segmentation based upon the statistics of the 2-D Gabor coefficients found by the relaxation network.

(d). Properties of Self-Similar 2-D Gabor Wavelet Representations

Building upon the relaxation network approach described above, several different schemes of image analysis and representation have been explored. Once the restrictive constraint of orthogonality has been lifted, many new approaches become possible which were previously prohibited by the lack of efficient means for obtaining the coefficients that constitute the image representation. Accordingly, we have explored several different image codes based on self-similar 2-D Gabor "wavelets," which obey a generative family of equations for self-similarity under dilation, rotation, and translation. Thus all members of this family can be generated by dilations and shifts of a single basic wavelet. A particular focus of work has concerned the trade-off between the numbers of discrete orientations employed in the representation, and the number of positions. We have shown that as long as the number of linearly independent degrees-of-freedom remains fixed, good image representations can be obtained with many different variations in the sampling rules for these dimensions.

All wavelet schemes, including the present non-orthogonal one, are parameterized by a geometric scale parameter m and position parameter n which relate members of the family to each other. In the classic one-dimensional case extensively studied by French mathematicians Yves Meyer, Ingrid Daubecies, Alex Grossmann, and

Stephane Mallat,

$$\Psi_{mn}(x) = 2^{-m/2}\Psi(2^{-m}x - n). \tag{1}$$

Generalizing to two dimensions and incorporating discrete rotations θ into the generating function, together with shifts p, q and dilations m, the present 2-D Gabor "wavelet" set can be generated from any given member by:

$$\Psi_{mpq\theta}(x, y) = 2^{-m}\Psi(x', y') \tag{2}$$

where

$$x' = 2^{-m}[x\cos(\theta) + y\sin(\theta)] - p \tag{3}$$

$$y' = 2^{-m}[-x\sin(\theta) + y\cos(\theta)] - q \tag{4}$$

By using the relaxation network to find optimal coefficients on this self-similar multi-resolution wavelet scheme, in which 2-D Gabor elementary functions serve as the $\Psi_{mpq\theta}(x, y)$, we have been able to explore many new aspects of orientation-based, multi-scale, self-similar image codes.

One recent application of these principles is an iris-based biometric signature security system for automatic visual personal identification. This very efficient algorithm establishes the identity of an individual in less than a second by examining the detailed textural structure of his iris, registered by a telescopic videocamera as an "optical fingerprint" without any physical contact. The detailed iris structure is extracted at many scales of analysis by projection into coefficients on a self-similar set of quadrature 2-D Gabor functions. A working prototype of this .nachine has been built and demonstrated to representatives of Federal security agencies. Preliminary tests show that this "biometric signature security system" outperforms all other automatic personal identification systems by about an order-of-magnitude.

PART VI

Rowland Institute Summary

Traditional Form and Motion Stimuli Presented to Isolated Cone Classes

Robert L. Savoy and **Michael M. Burns**

Rowland Institute for Science
100 Cambridge Parkway
Cambridge, MA 02142

Two ideas are explored, both of which concern the organization of cone classes in the subsequent connections of the visual system.

1: *The simplest notion of isoluminance is problematic.* If isoluminance is determined by a weighted sum of the input from individual cone classes then all the phenomena reported to occur with isoluminant stimuli should be present whatever the spectral composition of the colors used. Thus, for example, the disappearance of the kinetic depth effect should occur equally well using green dots on a grey background or green dots on a red background. Our work demonstrates that this is not the case. Using both subjective and objective criteria, the quality of isoluminance matches (and the psychophysical phenomena associated with isoluminant stimuli) vary dramatically with the spectral composition of the colored stimuli. The subjective measure is simply the reported quality of match. The objective measure is the variability of isoluminance settings. In particular, when the colors are a grey and green, the accuracy (repeatability) of isolumance matches is extremely good—about 1% (as good as making a luminance match with a single hue). And subjects experience the match as being excellent—in the case of the kinetic depth effect, all sense of depth is lost at isoluminance. On the other hand, when the colors are a saturated red and saturated blue, the variability of isoluminance settings is much higher—about 15%. The subjective phenomena are much weaker as well. Subjects continue to experience such phenomena as the kinetic depth effect at all relative settings of the two colors (in contrast to some reports). This finding is robust across a number of criteria—the kinetic depth effect, stereopsis, hetereochromatic brightness matches, and flicker.

2: *It is possible (using computer generated stimuli) to present a broad range of traditional psychophysical stimuli so that only a single class of cones can be used in the perception of those stimuli.* This is an extension of the body of work done using the "cardinal" directions of color space, to use the term coined by Krauskopf, et al. Stimuli are designed so that the spatial and temporal pattern on (for instance) two of the three cone classes is uniform. The third cone class is presented with spatial and temporal patterns of arbitrary complexity. The simplest experiment is to measure the contrast threshold for detection of a spot by a single cone class. The results (which replicate the work of several other laboratories) reveal the cardinal directions to be one luminance-like channel and two color difference channels. More general stimuli are possible. For instance, one can present a random dot stereogram so that the pattern on the left eye is seen only by the long-wave cones while the pattern on the right eye is seen only by the middle wave cones. Stereopsis is still obtained (and can be quantitatively assessed, in terms of the contrast needed to be perceived). More than one intensity level can be presented at once, so that Mach Band patterns, Simultaneous Contrast patterns, and even Mondrian-like patterns can be presented to isolated cone classes. The only restriction is that the maximum contrast cannot be too large—about 15% on the long and middle wave cone classes and about 80% on the short wave cones. This limitation is imposed by the overlap of the cone pigment absorptions. These techniques for isolating the activities of cone classes have already been used in some neurophysiological work and promise to be a useful tool in determining connections in the visual system.

END